# Sweeping and shaking dwarf satellites

Lucio Mayer

Institute for Theoretical Physics, University of Zürich, CH-8057 Zurich, Switzerland

James Wadsley

Department of Physics & Astronomy, McMaster University, Canada

### Abstract.

We present the first high-resolution N-Body/SPH simulations that follow the evolution of low surface brightness disk satellites in a primary halo containing both dark matter and a hot gas component. Tidal shocks turn the stellar disk into a spheroid with low  $v/\sigma$  and remove most of the outer dark and baryonic mass. In addition, by weakening the potential well of the dwarf tides enhance the effect of ram pressure, and the gas is stripped down to radius three times smaller than the stellar component. A very low gas/stars ratio results after several Gyr, similarly to what seen in dwarf spheroidal satellites of the Milky Way and M31.

# 1. Introduction

One of the most striking properties of the Local Group (LG) and other nearby groups is the morphological segregation shown by its galaxy members. Dwarf irregulars (dIrrs) are mostly found at distances > 300 kpc from the Milky Way and M31, while dwarf spheroidals (dSphs) and dwarf ellipticals (dEs) are clustered around the latter (Mateo 1998). Tidal stirring of disk-like dwarfs once they fall into the halo of the primaries at high redshift provides a way to transform their stellar component; a rotationally supported disk like that of dIrrs is heated by tidal shocks and by an induced bar-buckling instability, and simultaneously loses mass, turning into a pressure supported spheroidal of lower luminosity (Mayer et al. 2001a,b, hereafter MA01a,b). The periodic bursts of star formation seen in some dSph satellites of the Milky Way can also be explained as being triggered at pericenter passages (MA01a). However, stripping by tides plus gas consumption from star formation yields final gas fractions an order of magnitude too high compared to the limits inferred for dSphs (MA01b). A gas-poor dwarf can be the outcome of heating by the cosmic UV background (Bullock, Kraytsov & Weinberg 2000), but models of the tidal mass loss (Taffoni et al. 2003) suggest that the progenitors of Fornax, Sagittarius or the dEs satellites of M31 were too large  $(V_c > 50 \text{ km/s})$  for photoevaporation to be effective.

Recent new observational constraints coming from X-ray and UV absorption measurements suggest that the Milky Way has a hot gaseous corona with a mean density  $2 \times 10^{-5}$  atoms cm<sup>-3</sup> within 150 kpc (Sembach et al. 2003). Ram

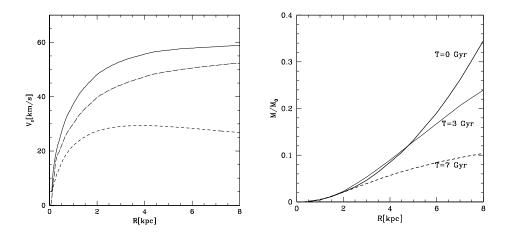


Figure 1. Left: rotation curve of the initial dwarf model. The solid line shows the global curve, the dot-dashed line the contribution of the dark matter and the short-dashed that of the disk. Right: evolution of the mass profile of the gas (normalized to the initial total gas mass) in the run in which  $n_H = 8 \times 10^{-5}$  atoms/cm<sup>3</sup> at 50 kpc.

pressure in a tenuous hot halo could remove the gas of dSphs at their present densities (Blitz & Robishaw 2002; Gallart et al. 2001). However, the current structure of dSphs does not reflect the initial conditions because they have been deeply affected by tides. Here we present results from new simulations that follow a disk-like dwarf orbiting in a "live" MW-sized halo with both a dark matter and a hot gas component, witnessing for the first time the combined effect of tides and ram pressure.

#### 2. Initial Conditions

Both the primary and the dwarf satellite are modelled according to current galaxy formation models in the LCDM cosmogony (Mo, Mao & White 1998). The primary (dark+hot gas) halo is based on the Milky Way (see Mastropietro et al., these proceedings). Its rotation curve peaks at 220 km/s. The gaseous halo density at 50 kpc is either  $2 \times 10^{-5}$  or  $8 \times 10^{-5}$  atoms/cm<sup>3</sup>, within the observational constraints. The dwarf has a dark (NFW) halo with  $V_{vir} = 50$  km/s, a stellar and a gaseous component. The gas accounts for 30% of the total disk mass (this is 4% of the virial mass) and has a mean density  $\rho_g \sim 10^{-3}$  cm<sup>-3</sup>, as found in LG dIrrs (Grebel, Gallagher & Harbeck 2003).

The halo has a low concentration, c=4, as required to match the rotation curves of dIrr galaxies (Swaters et al. 2003). The spin parameter is  $\lambda=0.043$ , resulting in a disk scale length of 2 kpc, and the B band central surface brightness, assuming a stellar mass-to-light ratio  $M/L_B=2$ , is 23 mag arcsec<sup>-2</sup>. The orbit has a pericenter of 50 kpc and an apocenter of 250 kpc, such eccentricity being typical for satellites in cosmological simulations. With the exception of Leo I and Leo II, the orbits of LG dSphs are much closer to the primary galaxies

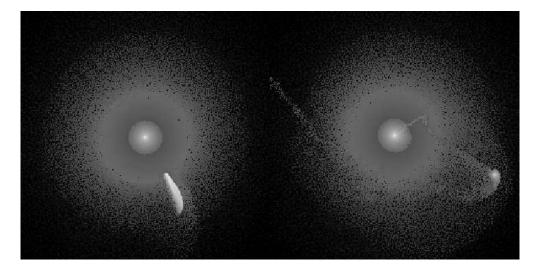


Figure 2. Gas density close to first pericenter (left) and second pericenter passage (right). Boxes are 100 kpc on a side, brighter regions correspond to higher densities.

compared to our choice, hence our results on the effect of tides and ram pressure will be on the conservative side. Overall the simulations use 1.85 million particles of which most of them are in the primary halo to minimize two-body heating against the lighter particles of the dwarf (Abadi, Moore & Bower 2000). The dwarf has 300,000 particles in the halo and 50,000 (20.000 gas and 30.000 star particles) in the disk. The simulations are carried out with the parallel Tree+SPH code GASOLINE (Wadsley, Stadel & Quinn 2003) without radiative cooling.

### 3. Results

The dwarf galaxy is evolved for 7 Gyr (about 2 orbital times) in the primary potential. Close to pericenter the gaseous disk begins to be ablated by ram pressure (Figure 2), simultaneously being distorted and turned into a non-axisymmetric shape by the tides. A bar forms in the stellar component which torques the gas, funnelling the latter inwards on a dynamical timescale as reported in previous simulations. The gas inflow counteracts stripping by tides and ram pressure, momentarily increasing the gas mass within the inner 4 kpc, while the outer disk is being completely removed (right panel in Figure 1).

After the second pericenter passage, however, ram pressure stripping has been efficient enough to remove the gas down to 2.5 kpc (Figure 1); such a stripping radius is almost 3 times smaller than that expected from ram pressure in absence of tides (Blitz & Robishaw 2001). At the end of the simulation the system resembles a gas-poor pressure supported dSph; the measured central  $v/\sigma$  has dropped to less than 0.3,  $\sigma \sim 20$  km/s, between 80 and 90% of the gas has been removed depending on the halo density, while only 30% of the stars have been stripped by tides, and the dark matter still accounts for about 80% of the

mass. The final gas mass within the gravitationally bound component of the galaxy is 5-7% of the mass in stars; this is roughly a factor of 4-5 lower than previous simulations which included only tides (MA01b). The upper limit on the HI/stars mass ratio in Local Group dSphs is still a bit lower, about 3%, but we cannot exclude that there is as much as 10% of the stellar mass in the form of a warm ionized component (Grebel, Gallagher & Herbeck 2003).

### 4. Conclusions

These simulations show that a model with tides and ram pressure in a tenuous hot Galactic corona is able to produce a very low gas-to-stars ratio in a dwarf satellite after a few orbits. However, it remains to be seen if the same model can bring down the gas fraction by another factor of ten and match the HI/stars ratio of Draco and Ursa Minor ( $\sim 0.1\%$ ); in principle this is possible because their progenitors were likely at least ten times lighter and their orbit located much closer to the Galaxy compared to the system simulated here (MA01b). In addition radiative cooling and star formation should be included in the simulations; however, new runs still in progress suggest that their combined effect leaves the final gas fraction almost unchanged, as the larger amount of gas retained by the satellite thanks to cooling compensates for the fraction that is turned into stars. Instead, a clumpy ISM and diffusion through the interface between the cold disk and the hot ambient medium induced by Raleygh-Taylor instabilities (not captured by SPH at the current resolution) could enhance significantly gas stripping (Quilis, Moore & Bower 2000).

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